Limits on Radiative Capture γ-Ray Lines and Implications for Energy Content in Flare-Accelerated Protons

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Abstract. Measurements of radiative capture γ-ray lines can provide information on both the energy content of nonthermal protons below 1 MeV and the temperature in the region where they interact. We have derived upper limits on the fluences in three proton capture lines of ^{12}C and ^{13}C in the flare-averaged gamma-ray spectrum from 19 X-class flares observed with the *Solar Maximum Mission* (*SMM*). The most significant limit comes from the 2.37 MeV line that is excited by 0.46 MeV protons. We estimate an upper limit on the energy content in the accelerated protons by extrapolating the power law spectrum derived at higher energies down to the resonant energy. The derived upper limit on the temperature, $\sim 5 - 10 \times 10^7$K, is higher than measured in the flaring region with other techniques, even for this optimistic energy content. It is possible that NASA's *High Energy Solar Spectroscopic Imager* (*HESSI*) will be sensitive enough to detect the 2.37 MeV line if temperatures exceed $\sim 2 \times 10^7$K.

Keywords: flares; proton acceleration; gamma-ray lines; flare energetics; temperatures

1. Introduction

Observations of high-energy radiation from solar flares indicate that both electrons and ions are accelerated during the restructuring of magnetic fields in the upper solar atmosphere (Forman, Ramaty, & Zweibel, 1986; Ramaty, 1986). Energetic electrons above $\sim$ 20 keV are responsible for X-ray and gamma-ray continuum emission, while interactions of ions with ambient nuclei account for nuclear deexcitation gamma-ray lines observed between $\sim$1–7 MeV, the 2.223 MeV neutron capture line, and the creation of positrons which produce the 511-keV positron-annihilation line.

While it is relatively straightforward to infer the energy content in accelerated electrons by analyzing hard X-ray bremsstrahlung (Brown, 1971; Lin & Johns, 1993), determining the energy content in low-energy

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14. ABSTRACT
Measurements of radiative capture γ-ray lines can provide information on both the energy content of nonthermal protons below 1 MeV and the temperature in the region where they interact. We have derived upper limits on the fluences in three proton capture lines of 12C and 13C in the flare-averaged gamma-ray spectrum from 19 X-class flares observed with the Solar Maximum Mission (SMM). The most significant limit comes from the 2.37 MeV line that is excited by 0.46 MeV protons. We estimate an upper limit on the energy content in the accelerated protons by extrapolating the power law spectrum derived at higher energies down to the resonant energy. The derived upper limit on the temperature, ∼ 5 − 10 ? 107K, is higher than measured in the flaring region with other techniques, even for this optimistic energy content. It is possible that NASA?s High Energy Solar Spectroscopic Imager (HESSI) will be sensitive enough to detect the 2.37 MeV line if temperatures exceed ∼ 2 ? 107K.

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protons from gamma-ray measurement is more uncertain. This is true because the strong de-excitation gamma-ray lines, used to infer the proton spectra, are only produced in interactions above a few MeV (Ramaty et al., 1995). Other methods have been explored to detect these low-energy protons. For example, Vogt, & Hénoux (1999) and Metcalf et al. (1994) have independently interpreted observed H_α linear polarization as evidence for impact polarization of chromospheric lines by <150 keV proton bombardment. Others (Orrall & Zirker, 1976; Canfield & Chang, 1985; Fang, Feautrier, & Hénoux, 1995) have also suggested that sub-MeV protons should give rise to Doppler-shifted emission in the Ly_α red wing through charge-exchange interactions with ambient hydrogen atoms. No detection supportive of this conclusion has yet been made on the Sun, although Woodgate et al. (1992) have seen broadened Ly_α profiles in a stellar flare with *Hubble Space Telescope.* The different sensitivity of the H_α line profile to electron or proton bombardment (Hénoux, Fang, & Gan, 1993)—namely an absence of central reversal with proton bombardment—provides yet another diagnostic for low-energy protons when used in conjunction with linear polarization measurements. However, these techniques rely on a number of assumptions, and they have not yet yielded unambiguous results.

The lack of direct observational evidence for the presence of low-energy protons in solar flares has led to some debate on the predominance of protons or electrons in the flare energy budget (Simnett, 1995). There is indirect evidence from *SMM* gamma-ray observations that imply low-energy (~ 1 MeV) protons may be much more important energetically than previously believed. Share & Murphy (1995) found that the flux of the 1.634 MeV gamma-ray line emitted by the ^{20}Ne isotope is enhanced in several X-class flares relative to other lines. Since this line has a comparatively low excitation threshold, such a high relative flux implies a proton spectrum that is much steeper than the flat Bessel function form previously assumed. Ramaty et al. (1995) revised their estimates of the low-energy ion flux by assuming that the spectrum extended as a power law down to 1 MeV and was flat at lower energies. Under these assumptions, they found that ions may have an energy content $\geq 10^{32}$ ergs in large flares (Ramaty & Mandzhavidze 2000), comparable to that estimated to be in the electrons responsible for the flare hard X-ray bursts (Miller et al., 1997) and more than an order of magnitude greater than previously inferred values. Trottet et al. (1998) found in a multiwavelength analysis that the upper limit on the energy content in > 1 MeV/nucleon ions rivaled that of the > 20 keV electrons even in an event which was electron-dominated (that is one which did not have detectable gamma-ray line emission).

Impulsive solar energetic particle events are generally associated with solar flares (Murphy et al., 1991). It is likely then that these particles in space are accelerated in the same processes that produce particles which interact at the Sun. Reames et al. (1997) have observed spectra from these events and find that the fluxes continue to increase down to 0.02 MeV/nucleon. They observed differential power-law spectral indices of ~ 2.5 at energies below 1 MeV. This demonstrates that particles below 1 MeV provide a significant contribution to the energy content of flare-accelerated ions in space.

What is required is a direct method for determining whether the power law spectrum of protons at the Sun continues to energies below 1 MeV without a break. Over a decade ago, MacKinnon (1989) suggested that proton capture lines from ^{12}C and ^{13}C might provide a direct radiation diagnostic of the energy content in sub-MeV protons. He found that the expected fluences in these lines are small and would only be substantial enough to warrant investigation for a "warm" target region and when the accelerated protons are energetically important. McConnell et al. (1997) used this method to set an upper limit of 2×10^{30} ergs s^{-1} on the energy input to the quiet corona from sub-MeV protons.

In this paper we set upper limits on the fluences of three radiative capture lines in solar flares using gamma ray data from the *Solar Maximum Mission* (*SMM*). From these limits we set constraints on the temperature in the interaction region as a function of the energy contained in flare accelerated protons.

2. Radiation Diagnostics of Sub-MeV Protons in a Warm Target

MacKinnon (1989) noted the possible utility of several direct radiation signatures of sub-MeV ions. He suggested the importance of radiative capture ($p - \gamma$) reactions of fast protons with ambient nuclei (denoted by X(p,γ)Y, where p is the incident proton captured by the target nucleus X, Y is the compound nucleus, and γ is the emitted photon). He noted that the gamma-ray yield from radiative capture of heavy ions is significantly smaller than for protons. The seven reactions he discussed have cross-section resonances at incident proton energies of a few hundred keV and produce discrete, well-defined gamma-ray lines. We list three of the most diagnostically important reactions in Table I, along with the proton resonance energy, E_r, and the resulting gamma-ray line energy. While detection of these capture lines may provide an independent assessment of the energetic importance of protons in

Table I. Lines Arising from p-γ Reactions

Reaction	Proton Energy E_r(MeV)	Line (MeV)	K (cm^{-2})
$^{12}C(p,\gamma)^{13}N$	0.46	2.37	6.03×10^{-41}
$^{13}C(p,\gamma)^{14}N$	0.555	8.07	8.18×10^{-42}
$^{13}C(p,\gamma)^{14}N$	0.555	4.12	6.64×10^{-42}

solar flares, the lines are relatively weak compared to other emitted gamma-ray lines.

If there are sufficient numbers of < 1 MeV protons, then the detectablility of these $p - \gamma$ lines ultimately hinges on the temperature of the interaction region (MacKinnon, 1989). In a "warm" target, the proton speeds become comparable with those of the electrons and the rate of proton energy loss in proton-electron collisions is consequently reduced; thus proton lifetimes, and gamma-ray yields, increase compared to the "cold" target case. For protons with a kinetic energy of 0.46 MeV, the "warm" target regime holds for temperatures from $\sim 5 - 500 \times 10^6$K.

MacKinnon discussed the details for estimating the gamma-ray fluences at Earth. The fluence in a given line is a function of temperature in the interaction region, the total number of protons with energy $E \geq E_r$ (the resonance energy), and the spectral index of the protons. In Table I we list the photon yield, K, that he derived at Earth from one proton interacting in a thick "cold" target . Even when 10^{38} protons are released in large flares, line fluences produced in "cold" regions close to the photosphere will be $\ll 1\gamma$ cm^{-2} and would not be detectable. However, temperatures in flare plasmas are known to exceed 10^7 K (Lin, et al., 1981; Feldman et al., 1995) and therefore the gamma-ray line yield will be considerably higher because of the reduced proton energy loss. Based on MacKinnon's calculations, we list estimated fluences in the most intense 2.37 MeV line in Table II for different energies contained in accelerated protons >0.46 MeV and temperatures in the slowing-down/interaction region. Gamma-ray detectors launched to date are typically sensitive to lines with fluences $\geq 1\,\gamma\,\mathrm{cm}^{-2}$. Thus either the temperature in the interaction region or the energy in protons would have to be high in order to produce a detectable radiative capture line flux. We expand on this in our discussion relating to our analysis of the *SMM* data below.

Table II. Expected Fluence in the 2.37 MeV Line. (γ cm^{-2})^a

Energy in Protons >0.46 MeV (erg)	Assumed Temperature 3×10^6K	10^7K	10^8K
10^{31}	0.00084	0.005	0.14
10^{32}	0.0084	0.05	1.4
10^{33}	0.084	0.5	14

^{a} for a power law with spectral index 4.8

3. Upper Limits on γ-Ray Line Fluences

Share & Murphy (1995) have studied nuclear line production in 19 flares observed by *SMM* from 1980 to 1989. They have also produced a summed spectrum from these flares to study weak line features that are not detectable in individual flares (Share & Murphy, 1998). We have used this summed spectrum in our effort to obtain limits on the (p,γ) lines produced at proton energies below 1 MeV. Before determining these limits, we first consider what we can learn about the interacting proton spectrum above 1 MeV. We use the ratio of fluences in lines from ^{20}Ne at 1.63 MeV and from ^{16}O at 6.13 MeV to determine the spectrum of protons above a few MeV. Ramaty et al. (1996) calculated the expected line ratios for different power law spectral indices and different assumptions about the compositions of accelerated particles and the ambient medium. Based on the Ne/O line ratio and the flare-averaged fluence in the ^{12}C line at 4.44 MeV, we have calculated the average interacting proton spectrum at the Sun for the 19 flares

$$N_p(E) = \mathrm{A} \times 10^{37} (\mathrm{E}/\mathrm{E}_0)^{-\delta} \ \mathrm{protons\,MeV}^{-1}$$

where $\mathrm{E}_0 = 1$ MeV. This spectrum has been calculated for accelerated particles having the composition of impulsive solar energetic particles (Ramaty et al., 1996) and for two values of the accelerated α/p ratio, 0.1 and 0.5. The corresponding values of A are, 2.5 and 1.2 ($\pm 0.5, 1\sigma$), and of δ are, 4.20 and 4.85 ($\pm$0.2), respectively. If this spectrum continues without a break down to energies below 1 MeV, we estimate that there are (4.5 ± 0.3) and (1.8 ± 0.2) $\times 10^{32}$ ergs in accelerated protons >0.46 MeV for α/p ratios of 0.1 and 0.5, respectively.

In Figure 1 we show regions of the summed flare spectrum in the vicinity of the three radiative capture lines. The arrows show the locations of the lines. We fit the full spectrum from 0.3 to 8.5 MeV with incident photons consisting of a bremsstrahlung continuum and 23

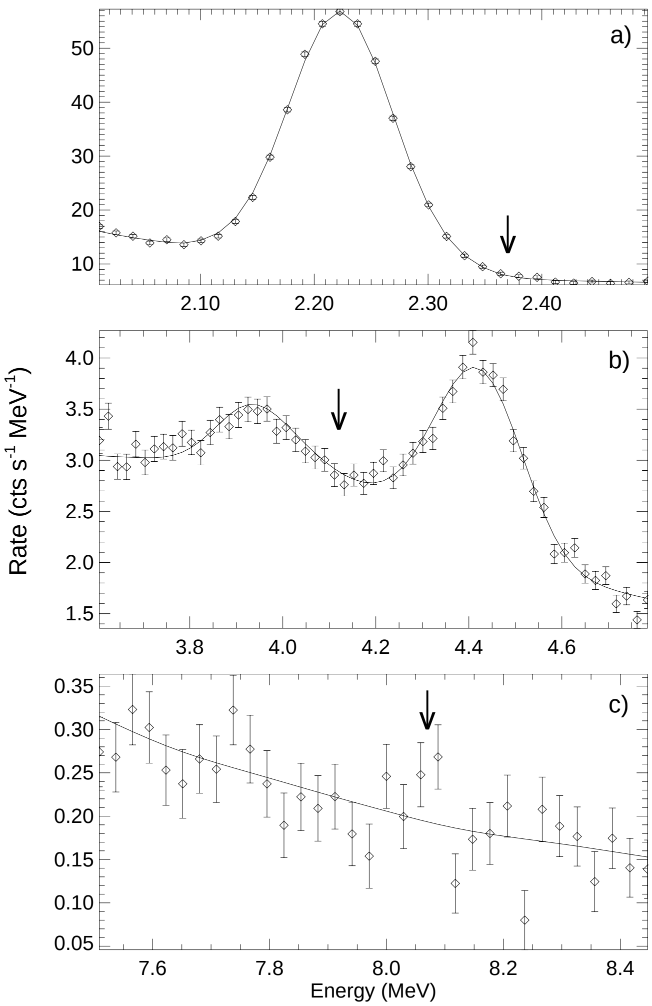

Figure 1. Fits to three regions of the summed spectrum from 19 *SMM* flares. Arrows indicate locations of the three proton capture lines.

Gaussian line features. The solid lines drawn through the data points show the best fits to the spectrum in the three energy ranges. The region near the 2.37 MeV line is dominated by the neutron-capture line at 2.223 MeV while the region near the 4.12 MeV line is dominated by the ^{12}C deexcitation line at 4.43 MeV and its first positron escape peak. There are no strong features near the 8.07 MeV line. We determined the best fitting fluences and their statistical uncertainties by varying the fluence in each line separately and monitoring the change in the value of χ^2. We fixed the energies and widths of the capture lines

(because the intrinsic widths are expected to be $< 1\%$, instrumental broadening dominates). We have therefore assumed that there is only one significant parameter. Under this assumption a 1σ change in fluence would produce a $\delta\chi^2 = 1$ and a 2σ change a $\delta\chi^2 = 3.8$ (Lampton, Margon, & Bowyer, 1976).

The best fitting average line fluences and 1σ statistical uncertainties for the 2.37, 4.12, and 8.07 MeV lines are (-1.15 ± 0.57), (-0.36 ± 0.36), and $(0.0 \pm 0.17)\,\gamma$ cm^{-2}. The 2 σ negative 2.37 MeV fluence may be due the inaccuracy of our assumed Gaussian approximation for the extremely strong 2.223 MeV line. Because of this possible systematic we take a conservative approach in estimating the 2σ (95% confidence) limit at 2.37 MeV; we set this limit as twice the absolute value of the fitted fluence. This limit is also what we obtain by performing a fit over a limited energy range in the counts spectrum from 2.0 to 2.45 MeV using a quadratic continuum and Gaussian lines at 2.223, 2.29 and 2.37 MeV. The line near 2.29 MeV appears to be required and could in part be due to ^{14}N. We obtain the 95% confidence limits on the fluences in the 4.12 and 8.07 MeV lines based purely on the statistical uncertainties. The resulting 95% confidence fluence limits are given in Table III.

We have studied whether the line limits can be improved by fitting data from individual flares or groups of flares. None of these efforts, including limiting our study to flares with the highest extrapolated energy content, improved on the results obtained with the flare-averaged spectrum. In an attempt to remove the possible systematic due to the neutron capture line, we only summed data from flares near the limb of the Sun, where the line is attenuated. Our fits to the 2.37 MeV line did not yield improved line limits due to the reduced statistics. Furthermore, restricting our fits to flares with weak emission > 7 MeV did not improve our limit on the 8.07 MeV line because most of the statistical uncertainty in this energy range comes from the subtracted background and not from the flare.

It is clear upon comparing the limit for the 2.37 MeV line with the expected fluences from Table II for $\sim 10^{32}$ ergs in total proton energy >0.46 MeV, that temperatures in the interaction region would have to be $\sim 10^8$K to produce a detectable line. The limitation of the current data is better visualized when we plot curves of the inferred temperature versus energy in protons for the limits placed on the fluences in the three lines. Following MacKinnon (1989) we plot the temperature in the interaction region as a function of the proton energy content for the three fluence limits in Figure 2. The shaded region highlights the estimated range in average energy contained in protons (>0.46 MeV) in the 19 *SMM* flares for α/p of 0.1 and 0.5, assuming that the power

Table III. 95% Confidence Capture-Line Limits

Line (MeV)	Fluence (γ cm^{-2})
2.37	2.3
4.12	0.7
8.07	0.35

law spectrum is extrapolated to low energy without a break. This range in proton energy content is consistent with intense flares observed to date; for example, observations of the 1991 June 4 flare by the *Compton Observatory* OSSE instrument indicated that there were $\sim 5-10\times10^{32}$ ergs in accelerated protons (Murphy et al., 1997). We have performed fits to the OSSE data from this flare but the line limits from the 19-flare spectrum still set the most sensitive constraints on temperature and energy. The 2.37 MeV line is the most sensitive line from the SMM data, even with its conservative limit due to its proximity to the neutron capture line.

4. Discussion

We have studied moderate resolution gamma-ray spectra in order to obtain limits on three radiative capture lines that can provide information on flare accelerated protons below 1 MeV. The best limits come from summing the spectra from 19 GOES X-class flares observed by the *SMM* spectrometer (Share & Murphy, 1995). The most constraining limit was derived using the 2.37 MeV line produced in the ^{12}C(p,γ)^{13}N resonance reaction of 0.46 MeV protons. Because of possible systematic effects we place a conservative 95% confidence limit on the mean fluence in the line of 2.3 γcm^{-2}; this exceeds the formal 2σ limit by a factor of two. Under the assumption that the derived power-law spectrum can be extrapolated below 1 MeV *without a break*, we estimate a mean energy contained in flare-accelerated protons >0.46 MeV. MacKinnon (1989) has developed the formalism for estimating the resonant γ-ray line yields as a function of the energy in accelerated protons and temperature in the particle interaction region. The locus of temperatures and proton energies consistent with our 2.37 MeV line limit is shown by the solid curve for *SMM* in Figure 2. Our line limit suggests that

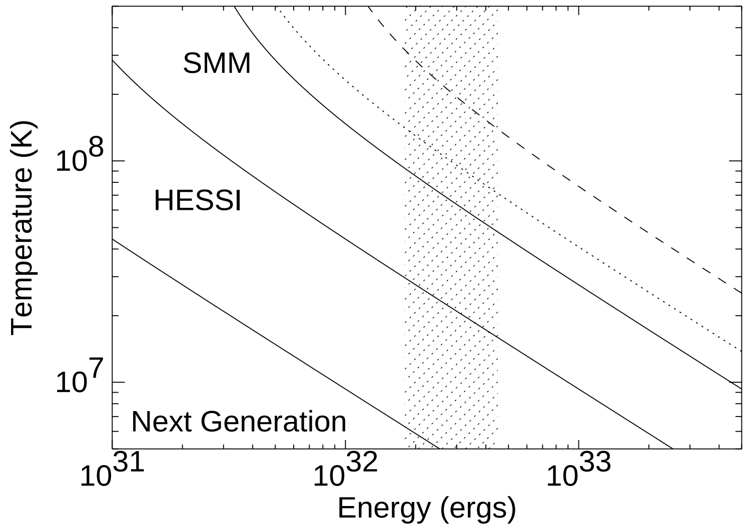

Figure 2. Interaction region temperatures and accelerated proton energies for the 95% upper limits on the three proton capture lines obtained from the flare-averaged *SMM* spectrum: 2.37 MeV – solid curves; 8.07 MeV – dotted curve; 4.12 MeV – dashed curve. Shaded region shows mean energy in protons assuming an unbroken power law down to 0.5 MeV and for accelerated α/p ratios of 0.1 to 0.5. Curves for expected 2.37 MeV line limits are shown for HESSI and a next generation gamma-ray spectrometer.

temperatures did not exceed $50 - 100 \times 10^6$K. Although of course if the proton spectrum flattens below a few MeV, then the inferred temperature limit would be significantly higher. This range in temperature is just few times higher than temperatures inferred in X-ray plasmas in flares greater than GOES Class M5 (Lin, et al., 1981; Feldman et al., 1995). We also note that a temperature $\geq 5 \times 10^6$K in the region where positrons, produced in nuclear reactions, annihilate was inferred from the 0.511 MeV line width for one flare (Share, Murphy, & Skibo, 1996).

A key question is whether it is the sub-MeV ions or 20 keV electrons that heat the flare plasma (Simnett, 1995; Emslie et al., 1996; Emslie et al., 1998; Mariska, Emslie, & Li, 1989) to temperatures in excess of 10^6K. It is reasonable to ask whether future gamma-ray experiments will have the capability of resolving this question. As the capture line widths are expected to be significantly less than 1%, high resolution gamma-ray spectrometers offer the potential for improved fluence limits. The *High Energy Solar Spectroscopic Imager* (Lin, 2000) is scheduled to be launched in 2001. Its spectral resolution of $\sim$3 keV is comparable to the widths expected from the lines. We estimate that

it should be at least a factor of 5 more sensitive to the 2.37 MeV line than the *SMM* spectrometer. The locus of temperatures and proton energies consistent with this improvement are shown in Figure 2. Thus, detection of the 2.37 MeV line with *HESSI* may be possible for temperatures exceeding $\sim 2 \times 10^7$K and energies in accelerated protons exceeding 10^{32} ergs. More likely it will require the additional ten-fold improvement in sensitivities expected from the next generation of γ-ray detectors (Kurfess, Johnson, Kroeger, & Phlips, 2000) before we may answer fundamental questions concerning the energetics of sub-MeV protons accelerated in solar flares with this technique.

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